

Comparison of Hyper-X Mach 10 Scramjet Preflight Predictions and Flight Data

Presented by

Paul G. Ferlemann

Swales Aerospace, Inc.

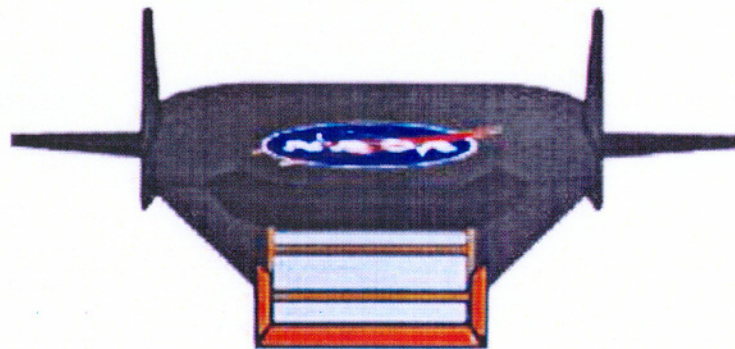
NASA Langley Research Center

Outline

- Vision vehicle
- Engine design process
 - Analytical
 - Experimental
 - Data analysis ➡ combustor performance model
- Flight vehicle propulsion database
- Hyper-X flight 3 scramjet propulsion test
 - Surface pressure
- Conclusions
- Acknowledgments

Vision Vehicle

- Dual-Fuel Global Reach vehicle.
- Cruise at Mach 10.
- Hypersonic cruise lifting-body configuration.
- X-43 = 6% scale.
- Demonstrating cruise capability with a subscale vehicle very challenging.
- Re-engine the X-43 Mach 7 vehicle.



Initial Engine Design Process

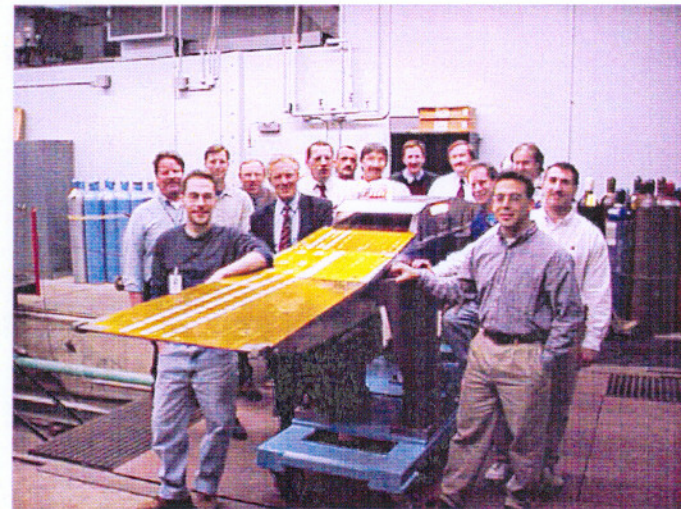
- Engine redesigned not scaled down.
- Vehicle already defined ➡ many constraints.
- Aero database existed ➡ design for vehicle performance.
- Two stage analytical approach.
- First stage: SRGULL tip-to-tail cycle analysis.
 - 3D spillage, η_{KE} , η_c , base pressure
 - M_∞ , α , q_{bar} , + 5 geometry variables
- Second stage: GASP & SHIP CFD.
 - Focused on fuel injector design
 - Thermal analysis performed for injector survivability

Wind Tunnel Engine Testing

- Unable to test ignition sequence ➡ separate tests with a silane-hydrogen mixture & pure H₂.
- HyPulse reflected shock tunnel
 - Partial width and truncated forebody and aftbody sections
 - Semi-direct connect test configuration
- LENS reflected shock tunnel
 - Full flowpath model with 2D forebody and aftbody sections
 - Free-jet test configuration
- All testing showed a sensitivity to fuel composition ➡ design modified to improve hydrogen only combustion.

Final Engine Testing

- HyPulse: 55 runs at 8 test conditions
 - Mach 9 total enthalpy
 - Mach 10 total enthalpy in 6 configurations
 - Mach 10.3 total enthalpy
- LENS: 20 runs at 4 test conditions
 - Low, nominal, and high dynamic pressure
 - 2° AoA at nominal dynamic pressure

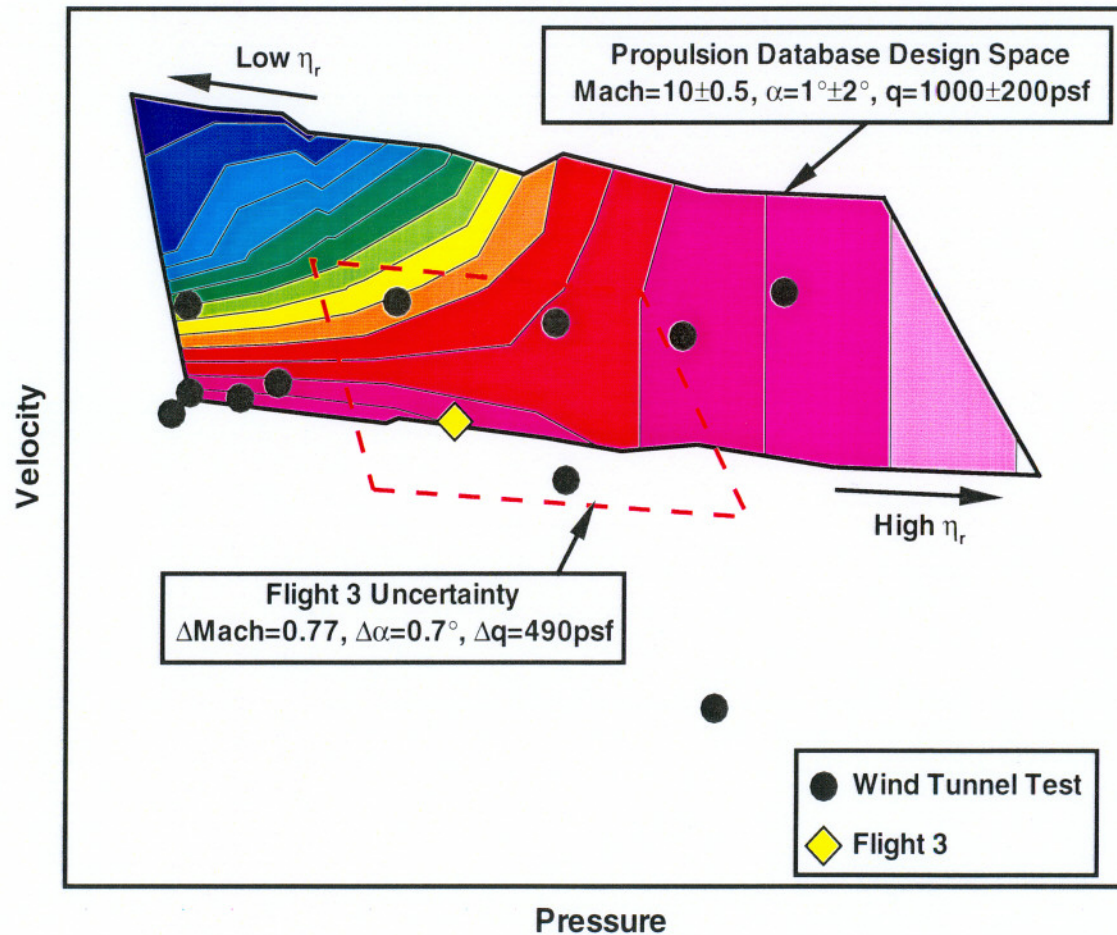


Engine Test Data Analysis

- Consistent methodology applied to every test.
- Goal ➡ determine combustion efficiency.
- GASP – forebody and inlet.
 - 2D, blunt leading edges, transition guided by heat flux data
- SHIP – injectors, combustor, and nozzle.
 - 3D PNS, center slice, 1-step reaction model
 - $\eta_c = \eta_m \cdot \eta_r$
 - η_r schedule determined by matching discrete pressure distribution in the combustor
 - Final η_r based on internal nozzle axial force
 - Relatively easy to perform analysis for silane-hydrogen mixtures

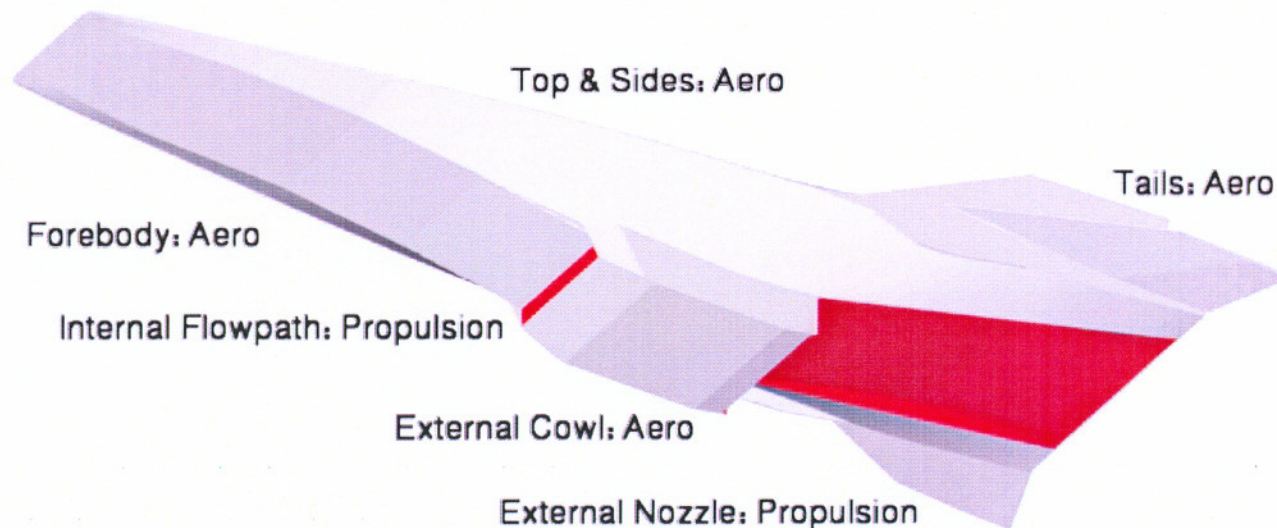
Combustor Performance Model

- Model created from analysis of engine test data



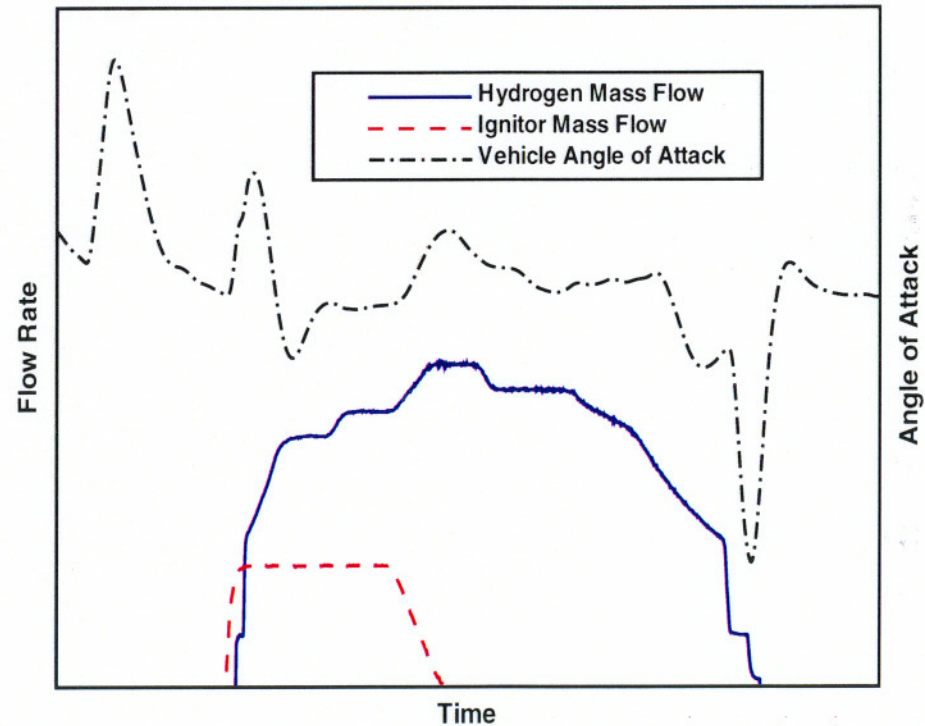
Flight Vehicle Propulsion Database

- Provide engine mass capture, propulsion surface forces and moment over a design space of Mach 9.5 to 10.5, angle of attack -1° to 3° , and dynamic pressure 800 to 1200 psf for both unfueled and fueled conditions.
- CFD database $f(M_\infty, \alpha, q_{bar}, \phi, \eta_r)$.



Overview of Flight Test

- Engine fueling sequence designed to match engine wind tunnel test composition and levels.
- Ignitor and H_2 to high levels quickly.
- Gradual transition to pure H_2 .
- Well controlled.
- Duration = 50 times longer than sum total of all final engine tests.



The image contains two diagrams of a ship's deck layout, showing the positions of 70 numbered points (P001 to P070) relative to the Port and Starboard sides.

Top Diagram (Side View):

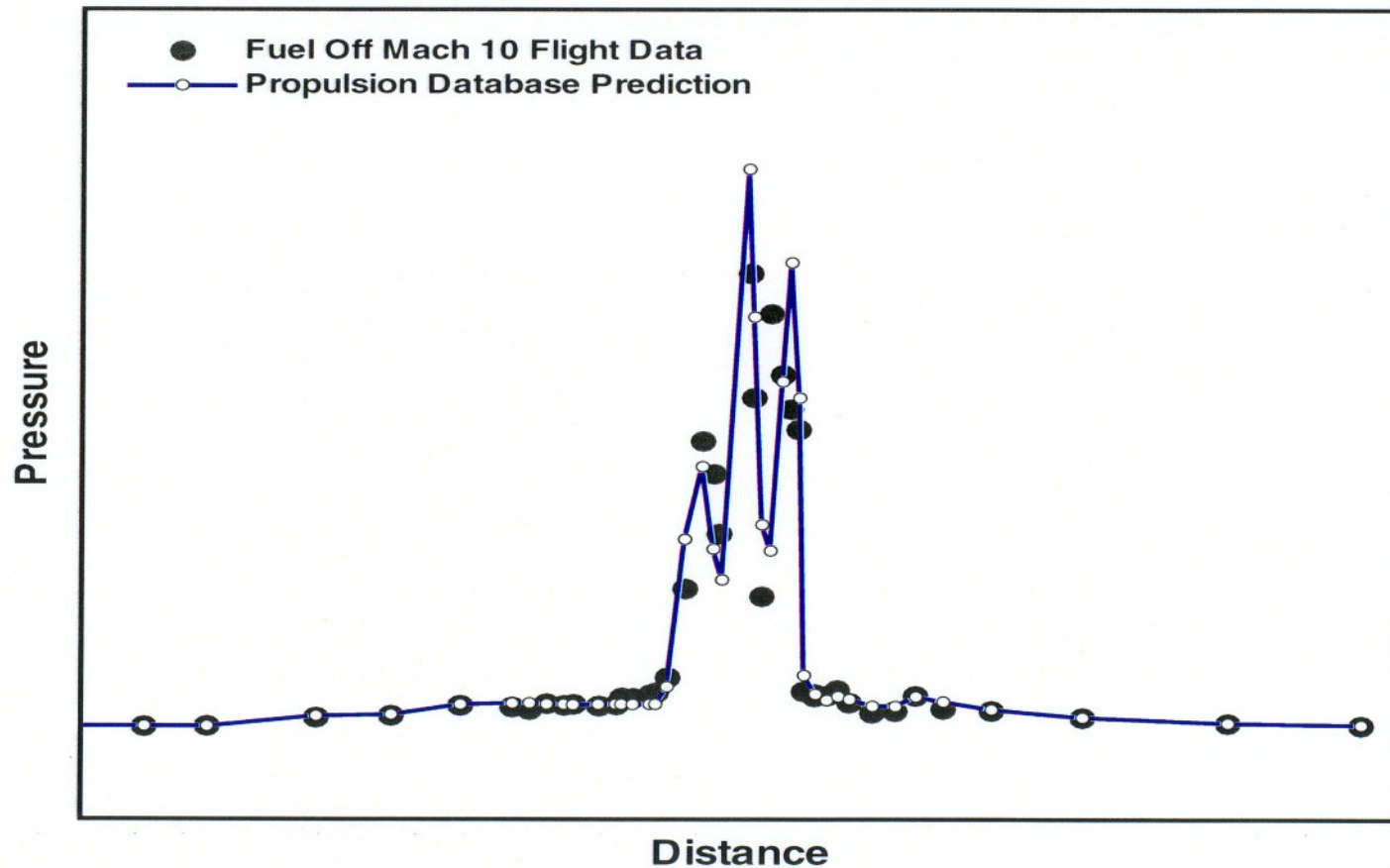
- Port Side (Left):** P093, P095, P001, P205, P206, P207, P208, P209, P210, P211, P218.
- Starboard Side (Right):** P246, P047, P257, P053, P272, P054, P058, P059, P263, P057, P258, P262, P273, P255, P259, P261, P256, P048, P051, P052, P055, P056.
- Central Area:** A cluster of points including P002, P007, P247, P256, P049, P051, P052, P055, P056, P255, P259, P261, P256, P048, P051, P052, P055, P056.

Bottom Diagram (Top-Down View):

- Port Side (Left):** P004, P216, P212, P213, P214, P215, P005, P217, P006, P219, P220, P008, P221, P302, P222, P225, P228, P232, P226, P227, P234, P235, P013, P014, P021, P022, P029, P030.
- Starboard Side (Right):** P249, P250, P251, P252, P253, P254, P255, P256, P257, P258, P259, P260, P261, P262, P263, P264, P265, P266, P267, P268, P269, P270, P271, P272, P273, P274, P275, P276, P277, P278, P279, P280.
- Central Area:** P229, P010, P018, P026, P223, P230, P011, P019, P027/P201, P037, P032, P035, P039, P041, P043/P203, P045/P204, P231, P236, P238, P240, P033, P224, P231, P236, P238, P240, P033, P225, P228, P232, P009, P012, P015, P023, P020, P024, P028, P031/P202, P034, P038, P040, P042, P044, P046, P245, P241, P242, P243, P244, P245, P246, P247, P248, P249, P250, P251, P252, P253, P254, P255, P256, P257, P258, P259, P260, P261, P262, P263, P264, P265, P266, P267, P268, P269, P270, P271, P272, P273, P274, P275, P276, P277, P278, P279, P280.

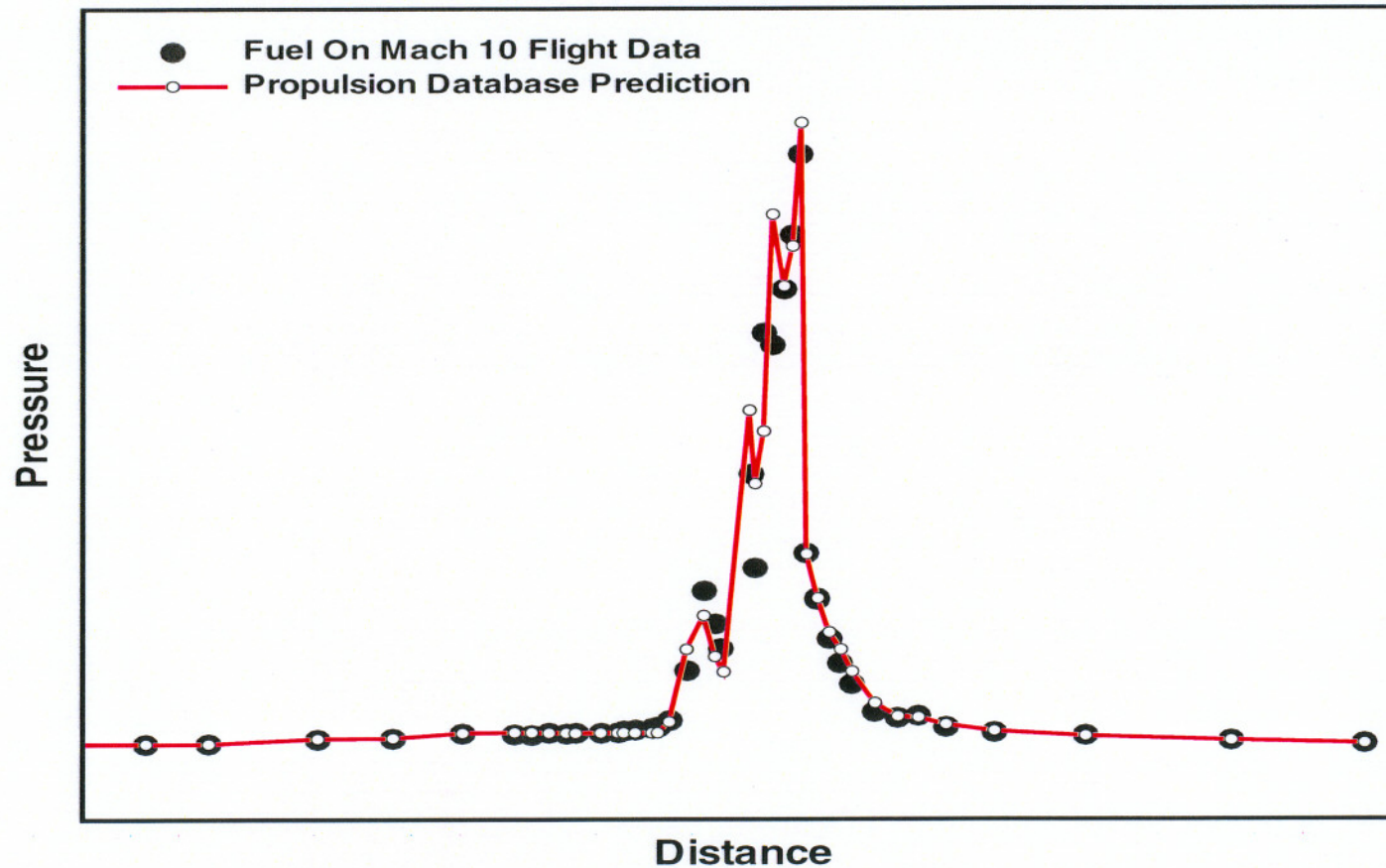
Centerline Pressure Fuel Off

- Shock-dominated flow.
- No nozzle pressurization.



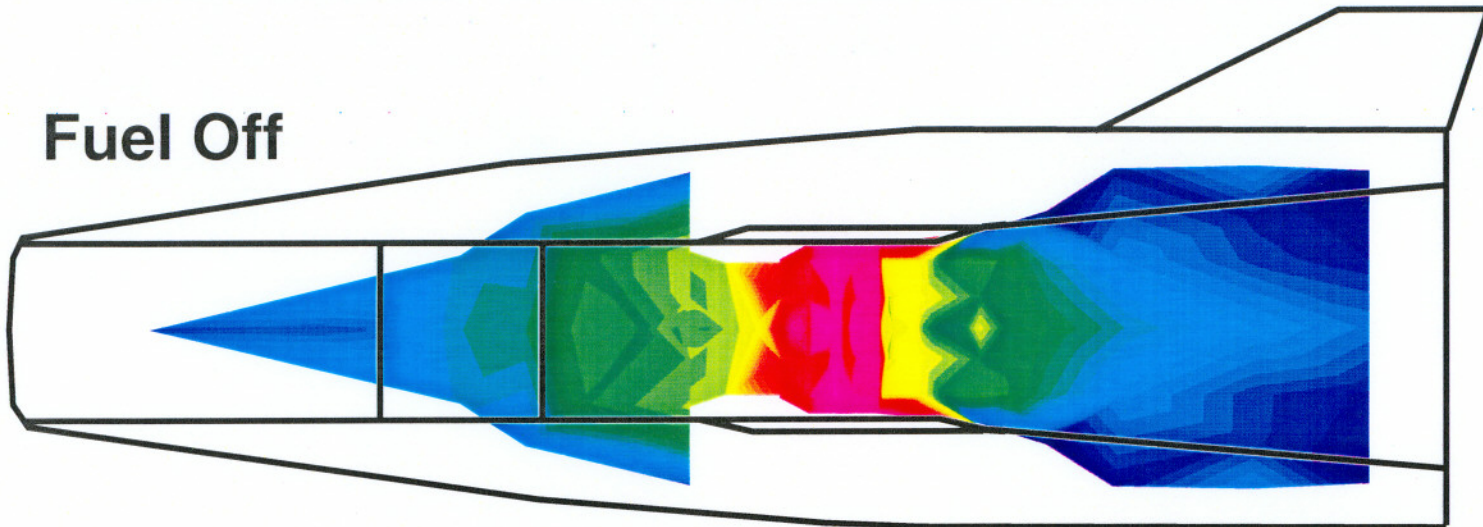
Centerline Pressure Fuel On

- Significant pressure rise.

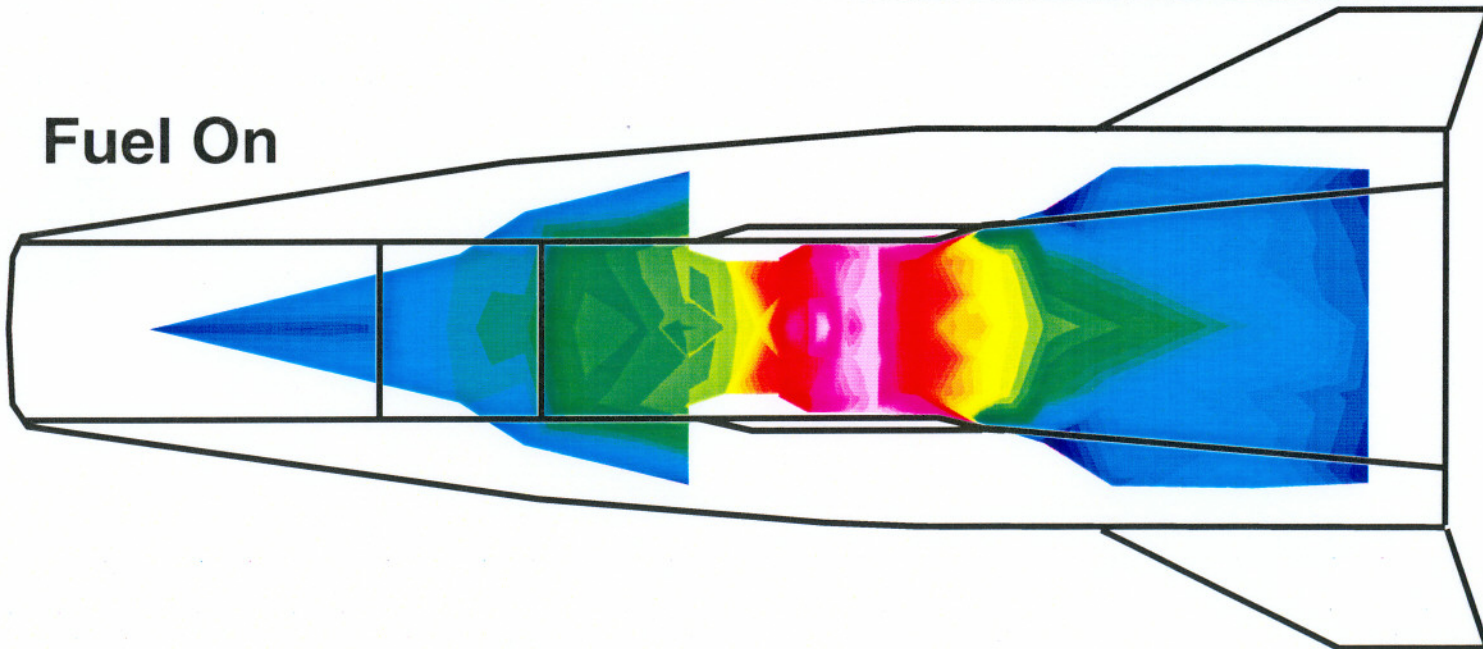


Surface Pressure Contours

Fuel Off



Fuel On



Conclusions

- The Hyper-X program's third X-43 vehicle demonstrated successful air-frame integrated scramjet operation and vehicle control at hypervelocity conditions.
- Good agreement with expectations is an important validation of propulsion testing in pulse facilities and in the computational techniques used to understand scramjet engine test data.
- Demonstrated cruise capability (subscale) at the design cruise Mach number of a vision vehicle, shows that a vehicle could be designed to accelerate through Mach 10 using an airbreathing engine.

Acknowledgments

- Randy Volland and Larry Huebner
— Hyper-X propulsion team leads
- Shelly Ferlemann — SRGULL calculations
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— GASP calculations
- Clay Roger, Ann Shih, and David Witte
— engine ground test program